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SCIENTIFIC LEADER OF THE EXPEDITION

VOLUME V

Sediment Cores from the East Pacific

FASC. II

Special Contributions

GÖTEBORG
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REPORTS OF THE SWEDISH DEEP-SEA EXPEDITION. VOL. V
SEDIMENT CORES FROM THE EAST PACIFIC

PART 5:1

PROPORTION OF SEDIMENTARY COMPONENTS IN THE CALCAREOUS EUPELAGIC AREA OF THE EAST PACIFIC

BY

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The East Pacific eupelagic sediments may be defined by their relative content of biogenous, hydrogenous and lithogenous components. The quantitatively important biogenous components are calcium carbonate tests and test fragments of foraminifera, calcareous plates of Coccolithophoridae, and further siliceous remains, mainly of radiolaria but also of diatoms, silicoflagellates, a. o. The opaline silica is to a certain extent peptized and converted into silica gel.

The hydrogenous phase (GOLDBERG 1954) is formed in the hydrosphere and includes the hydrolysates, oxidates, reduzates, precipitates and evaporates of the Goldschmidt classification (GOLDSCHMIDT 1945). A further subdivision of this component into marine and freshwater origin of the solid phase can be made. The pelagic clay minerals are believed to be largely marine precipitates, arising from ionic species of aluminum and silicon in sea water (ARRHENIUS 1954). The pelagic oxidates of marine origin include the hydrated oxides of manganese and iron. The iron is dominantly in particulate form in the ocean (COOPER 1937, LEWIS and GOLDBERG 1954), and the close correlation between iron and titanium in manganese nodules points to a hydrogenous origin of the titanium (GOLDBERG 1954). Goldberg believes that the titanium is scavenged by the iron. The particulate iron is used as a nutrient by lower members of the biosphere, which act as a reservoir for this element. Together with the iron also titanium and zirconium are concentrated from the sea water by the organisms. This phenomenon has been observed during bloom of flagellates (COLLIER 1953).

The lithogenous component, carried as a solid phase into the oceans from the lithosphere, includes Goldschmidt's resistates. It is represented in the eupelagic sediments by quartz and other igneous minerals, mainly in the coarse fraction.

Considerable interest has been devoted to the distribution of titanium in pelagic sediments, and it has been found (Vol. 5. ch. 1.2) that over certain areas of the Equatorial Pacific the rate of accumulation of this element has been remarkably uniform with regard to space in Middle and Late Pleistocene time. The titanium in the sediment may originate from several sources (cf. CORRENS 1954). It can therefore not be directly concluded from the uniformity observed, that also the rate of accumulation of other components of hydrogenous and lithogenous origin are uniformly distributed within the area and time interval in question. If they were, however, the concentration of titanium in the minerogenous part of the sediment would be essentially constant. To investigate the situation, we shall temporarily make the assumption that this holds true. The total concentration of minerogenous matter is in such a case x [TiO_2], where x is an unknown constant. We shall further assume that the concentration of radiolaria larger than 150 μ, [Rad], together with a constant z, corresponding to the concentration of silica gel, is linearily related to the total concentration of

biogenous silica in the sediment. The following equation should under such circumstances hold true on the average.

$$[CaCO_3] + x\,[TiO_2] + y\,[Rad] + z = 1 \quad (1)$$

An individual sample could not be expected to follow this formula exactly but should give a right hand side deviation from unity with a certain amount. By minimizing the sum of squares of these deviations as in the method of least squares, the »best» values of x, y and z can be determined. The resulting values are given in Table I.

In order to judge the goodness of fit, two methods have been used. First, the problem has been considered as that of determining the regression of $[CaCO_3]$ on $[TiO_2]$ and [Rad] simultaneously. From this view point x and y are the partial regression coefficients and the goodness of fit is measured by the multiple correlation coefficient R. The values of R given in Table I show a surprisingly good fit. Secondly, it is of interest to investigate whether the linear formula (1) is good enough or terms of higher order need to be introduced. Without involving heavy computations this problem can be attacked in the following way. The values of each sample are inserted into the left hand side of the corresponding equation (1), and a plus sign is written down if the resulting value exceeds unity, otherwise a minus sign is written down. For all samples of a core the number of plus signs and minus signs should be approximately the same. If,

TABLE I

Core	*No. of samples*	a[1])	x	y	z	R
58	114	70	1.37	—0.062	0.161	0.92
59	107	325	1.72	0.038	0.089	0.86
60	108	408	1.42	0.024	0.118	0.92
61	116	650	2.27	0.020	0.120	0.80
62	161	243	1.23	0.138	0.062	0.95
Total	606		1.37	0.038	0.110	0.92

[1]) a = accumulation (cm) from substage 5 to present time.

TABLE 2

Deviations from linear formula.
Numerator: Number of minus signs.
Denominator: Number of plus signs.

Core 61: $[TiO_2]$	*Radiolaria*			Total
	0—800	801—1600	1601—	
0—25	13/6	5/8	2/1	20/15
26—40	8/8	8/9	5/5	21/22
41—	3/1	5/7	10/10	18/18
Total	24/15	18/24	17/16	59/55

Core 58: $[TiO_2]$	*Radiolaria*				Total
	0—200	201—400	401—600	601—	
0—200 ...	8/2	7/6	4/3	3/2	22/13
201—300 ...	3/4	7/3	3/7	2/6	15/20
301—	0/4	7/7	6/2	8/9	21/22
Total	11/10	21/16	13/12	13/17	58/55

however, the samples are grouped after some rule, systematic deviations from formula (1) should be detected by considering the balance of plus and minus signs in each subgroup. In the present material core 58 and core 61 have been studied in this way. The samples have been grouped according to their $[TiO_2]$ and [Rad] -values (Table 2). It is readily seen that eventual systematic deviations from linearity are of negligible importance.

The good fit of the observations into equation (1) indicates that the assumptions expressed by this are statistically valid, and that the deviations in the proportion of titanium in the minerogenous matter from this specific area and time interval are small.

The distribution of values for x and y in Table 1 may give indications with regard to systematic deviations from equation (1). The relatively large variance of y suggests that inconsistencies in the assumption of the total mass of siliceous skeletal remains being directly proportional to the number of radiolaria larger than 150 μ, may be responsible for a large part of the deviations from the mean equation. Further there is an obvious correlation between x, and the average rate of accumulation a,

as given in the third column of Table 1. A probable explanation of this may be that the amount of siliceous fossil remains other than radiolaria is not constant or proportional to the amount of large sized radiolarian skeletons, as is assumed in the approximation, but is relatively increased in areas with a high rate of biogenous accumulation. This is confirmed by the fact that the relative concentration of diatoms is increased in the facies, which corresponds to a high rate of carbonate accumulation (Vol. 5, Fig. 1.9.2.4.). As no reliable methods exist at the present time of estimating quantitatively the total amount of biogenous silica, the approach to this problem had to be limited to the approximation expressed by equation (1). An excess of biogenous silica will in this equation partly enter into the term $x\,[TiO_2]$, causing a too high value of x.

Further investigations of these conditions are being carried out at the present time.

Summary

The good statistical fit of the experimental values into the assumed relationship between biogenous and minerogenous components of 606 Pleistocene eupelagic samples confirms the observed uniformity of composition of the minerogenous component. The conclusions are limited by the uncertainty in estimating the concentration of biogeneuos silica. The covariance of the regional average rate of biogenous accumulation on one hand and the apparent change in composition of the minerogenous component on the other, indicate that this change is not real, but simulated by variations in the rate of accumulation of biogenous silica from other sources than large radiolaria.

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REPORTS OF THE SWEDISH DEEP-SEA EXPEDITION. VOL. V
SEDIMENT CORES FROM THE EAST PACIFIC

PART 5:2

ON THE VARIATION OF THE GENERAL CIRCULATION OF THE ATMOSPHERE DURING PAST AGES

BY

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G. Arrhenius (1950, 1952 a, 1952 b) has discussed the climatic evolution in the East Equatorial Pacific. From a study of the bottom sediments Arrhenius has drawn certain conclusions concerning the rate of the low latitude circulation presented in Vol. 5.1, ch. 1.1 and in Vol. 5.1, ch. 3.4, and here will be given only a short summary of his studies and a discussion based on meteorological information.

The general atmospheric circulation is connected with the pressure distribution. Deep low pressure areas normally exist over the seas at 60° N and 60° S and a weak low a few degrees north of the equator. High pressure belts are situated over the seas at about 30°—40° N and 30°—40° S. There is a poleward shift of these pressure areas in the summer. Between the high latitude lows and the subtropical highs westerly winds predominate, and between the subtropical highs and the equatorial low the easterly trades are found. By frictional effects the trades transport water to the western part of the oceans where it is piled up against the continents. In the equatorial lows, where only a small windstress is acting, the water runs downslope as a mighty river from west towards the east. By this way is formed the Equatorial Counter Current as explained by Montgomery and Palmén (1940). Defant (1936) and Sverdrup (1942) have explained the distribution of temperature, salt and oxygen contents in the vicinity of the Counter Current as a result of vertical circulation (see fig. 2 a). Recently Cromwell (1953) has utilized extensive new data from the Pacific which do not support the existence of a divergence north of the

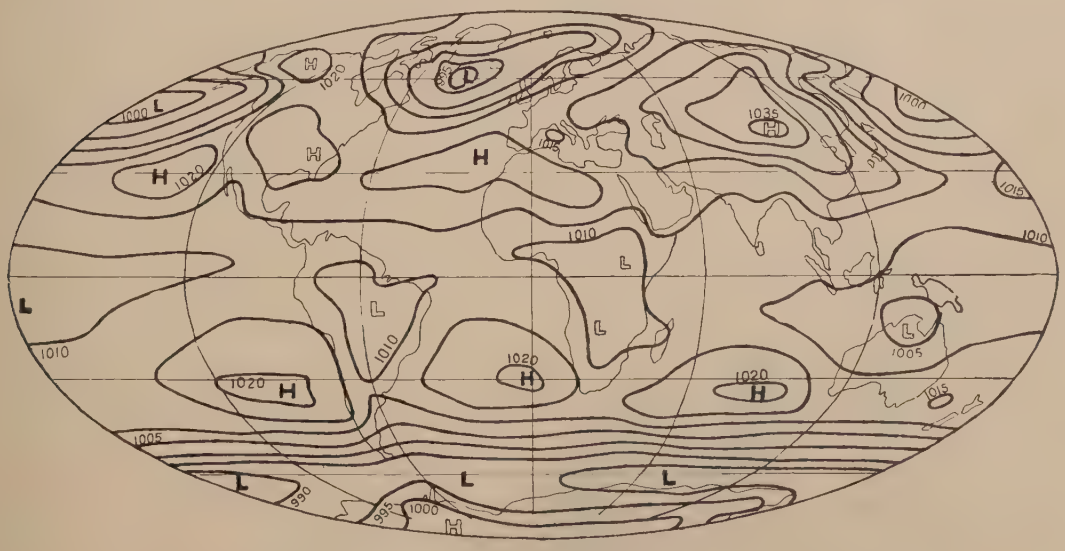

Fig. 1. Normal air pressure at sea level during January. After Bergeron.

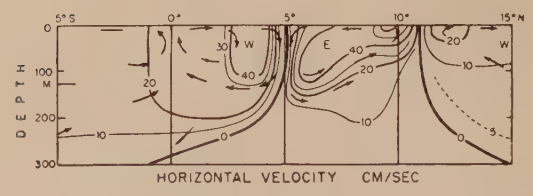

Fig. 2 a. North-south, and east-west flow in a vertical section between 5° S and 15° N in the Pacific Ocean according to the Defant-Sverdrup model. (From Sverdrup, Johnson, Fleming, 1946). Arrows indicate direction of north-south flow. E indicates flow to the east, W flow to the west.

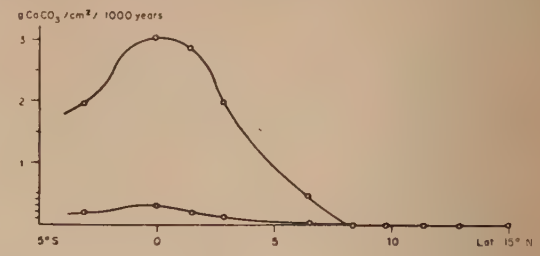

Fig. 2 b. Rate of accumulation of calcium carbonate on the ocean floor below the section of fig. 2 a. The upper curve corresponds to the circulation maximum 2 (supposedly Wisconsin Ice Age) and the lower curve to the circulation minimum 3 (supposedly Sangamon Interglacial). Rates are given in g/cm² in 1000 years. (Data from Arrhenius, 1952.)

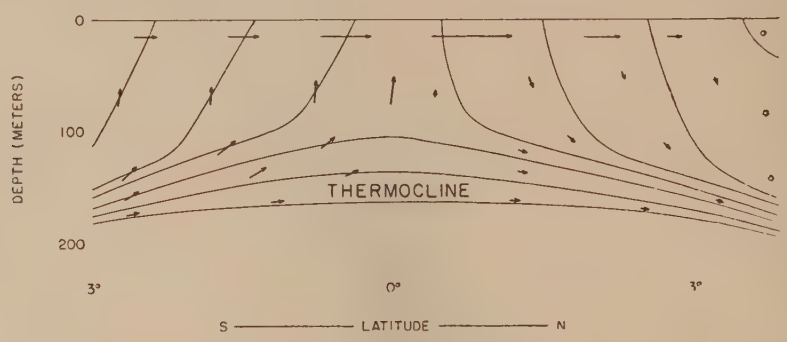

Fig. 2 c. Schematic representation of circulation in a meridional plan near the equator during a southeast wind, according to Cromwell (1953). Full lines indicate surfaces of constant density (σ_t) and the arrows indicate streamlines. Small circles indicate regions of slight and variable flow in this plane. Upwelling is indicated at and near the equator, the only region within the equatorial currents of the central Pacific where persistent upwelling occurs according to this author. (From Cromwell, 1953).

Counter Current at 10° N and an upwelling there. The main upwelling is found at the Equator (fig. 2 c), and is explained by Cromwell as resulting from the rapid change of the effect of the Coriolis force at and near the Equator.

The production of phytoplankton in the sea is largely influenced by the transport of nutrients into the surface layer and by the solar energy available for assimilation. Sufficient radiation energy is present only in the uppermost part of the ocean, where phytoplankton production is restricted largely by insufficient supply of nutrients. Where upwelling takes place, water rich in nutrients is supplied from deeper layers and the production of phytoplankton, and consequently of zooplankton, can be high.

The amount of calcium carbonate in shells and skeletons reaching the bottom is recorded in the sediment on the ocean floor. Arrhenius found that north of 9° N there is a negligible rate of accumulation of calcium carbonate during the Pleistocene period, whereas this rate is high south of 8° N. Arrhenius makes the assumption that the rate of accumulation of calcium carbonate microfossils depends, besides on the rate of dissolution of the carbonate particles before burial, on the intensity of the phytoplankton production and therefore on the rate of upwelling (surface water circulation), and further that the low latitude surface water circulation depends on the low latitude atmospheric circulation. That is to say the record of the calcium carbonate deposit is according to him ultimately a record of the past climate.

Arrhenius in his original work (1950, 1952) compared the rate of accumulation of biogenous sediment on the bottom with the features of productivity at the surface of the ocean, as indicated by Defant's model for vertical meridional circulation in the Equatorial Current System (fig. 2 a). He found a marked effect of the high productivity in the Equatorial Divergence on the rate of accumulation of plankton remains on the bottom below this divergence, but there were no indications in the sediment of the permanent existance of a North Equatorial Divergence at 8—10° N, as required by Defant's theory. Arrhenius later pointed out (personal communication) that a good agreement exists between the circulation model suggested by CROMWELL (1953), the standing crop of zooplankton according to KING and DEMOND (1953) and the rate of biogenous accumulation on the ocean floor as observed in the cores of the Swedish Deep Sea Expedition (ARRHENIUS 1952) and the Scripps Institution of Oceanography Expedition Capricorn, 1952—1953. Arrhenius therefore indicates that Cromwell's model accounts for the information gained from the sediment in a better way than the Defant model.

Let us discuss from a meteorological point of view some facts and theories which are concerned by this assumption.

MILANKOVIÇ (1930) in his theoretical climatology, tried to explain the past climatic variations by variation in the inclination of the ecliptic, and of the axis of the earth and by the precession of the equinoxes. An increase of the angle between the ecliptic and the equator would increase the heat supply in higher latitudes in the summer and thus tend to a poleward shift of the heat equator and also to a considerable shift of the equatorial divergence zone in a meridional direction repeated several times during the Pleistocene. Such a shift would then lead to an increased deopsition of calcium carbonate much farther to the north than has been observed. Arrhenius therefore can conclude that Milankovic's theory does not hold, which is also supported by other observations (WILLETT 1949).

One of Arrhenius' most important results is perhaps the variation with depth (or time) of the deposit. Periods corresponding to a deposit rich in calcium carbonate in a specific equatorial zone in the Pacific are supposed to be periods of increased water circulation as well as of increased atmospheric circulation in the trade wind belt. Arrhenius states that the rate of the surface water circulation has maxima at the times of known ice-ages and minima during interglacial periods. Is it possible to say anything about the atmospheric circulation?

We know that during summer the subtropic highs move polewards. At the same time they increase in intensity. The trade winds may be supposed to decrease as an effect of the poleward displacement of the highs. On the other hand the increase of the intensity of the highs is correlated with an increase of the trade winds. There are thus two different effects on the trade winds and as a matter of fact direct observations of trade winds in different parts of the oceans so far have given no conclusive results as to a seasonal variation of the trade wind branch of the general circulation.

It has been shown by AHLMANN (1949), LYSGAARD (1949), and others that the climate has become much warmer during the last half century in the polar regions. Polar ice is melting and most glaciers retreat. Lysgaard has computed the temperature changes for a number of isolated points. His figures (see fig. 3) show an increase of several degrees C of the January mean temperature in 60°—70° N whereas the temperature increase in the equatorial region (if any) is very slight. Lysgaard also has found certain pressure changes but he has drawn no conclusions as to systematic pressure changes in equatorial regions. A. SERRA (1948 and 1946) has computed

Fig. 3. Changes in January temperature from 1910 to 1940. After Lysgaard.

pressure charts for the whole hemisphere for two periods 1873—1909 and 1909—1934. I have tried to use these charts to find possible changes. The pressures have been evaluated for every 5th degree latitude and longitude over the Pacific and Atlantic Oceans and changes from the first to the second period have been plotted. Here will be discussed only the mean latitudinal changes.

It appears that for January both the subtropical highs have been slightly displaced polewards and their intensities have decreased from the first period to the second one. (see fig. 4). For July there have also been poleward displacements of the highs and the southeast trade wind has slightly decreased whereas there has been a slight increase of the northeast trade.

The value of this result seems to me to be rather problematic as the basic data for the charts are unknown to me, and the differences are small, and could be the result of inaccurate drawing of isobars on account of too few observations. I still present the results here as a weak indication of what may have happened. An interesting result by D. Fultz, University of Chicago, is worth mentioning in this connection. He has studied the circulation patterns obtained in a rotating hemispherical shell filled with a liquid, and communicated to me the following results. When the shell is heated in the »equatorial region» meridional cells are set up giving vertical circulation from the equator to about 20—40° latitude, whereas exchange of heat and momentum closer to the pole takes place mainly by horizontal eddies like the migrating cyclones and anticyclones in the atmosphere. If the heat supply increases the vertical cells get extended to higher latitudes (see fig. 5).

The same thing is likely to happen in the atmosphere. If the solar radiation increases, the temperature should increase everywhere and also the temperature difference in the upper atmosphere between the equator and the pole. This leads to an increased heat exchange and as a result some ice will melt at the pole. A small increase in solar radiation may have a corresponding small effect in the temperature in the equatorial region and a

much greater effect in the surface layers in the polar region. Compare the actual change in the last 80 years as shown by Lysgaard (fig. 3).

As to the probability of changes in the solar radiation the following can be stated. Most experts on solar radiation agree that it has not been possible to find any variation in the »solar constant», by direct measurements. However, the accuracy of the instruments is not high enough to exclude a variation of the »solar constant».

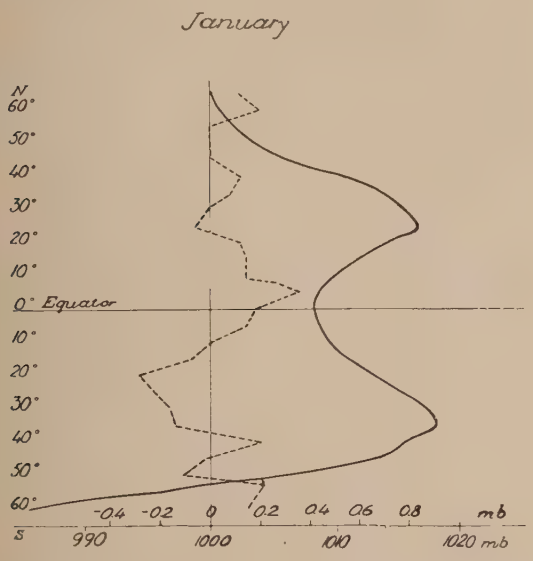

Fig. 4. Latitudinal variation of pressure over the Atlantic and the Pacific oceans, full line, and pressure changes over the same areas from the period 1873—1909 to the period 1910—1934, dotted line.

From astrophysics we know that the radiation from many stars undergoes strong changes. It seems probable that at least small changes should take place even on the sun, and if so the variation of the sun's total radiation may be the primary cause of most climatic changes.

Simpson has stressed the fact that the water vapor content in the air decreases with temperature. He concludes that a decrease of temperature therefore cannot lead to an increased glaciation. It does not seem justified to draw such a conclusion in the light of

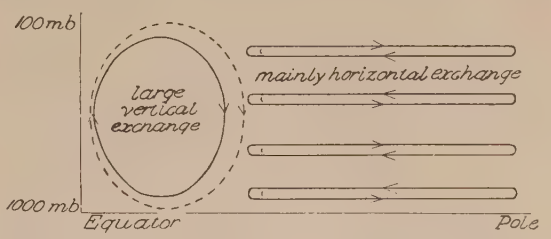

Fig. 5. Meridional cross-section of general atmospheric circulation. The dotted line indicates condition at increased solar radiation. 1000 mb corresponds to sea level, 100 mb to approximately 16 km.

what is known about the conditions favourable for increase or decrease of glaciers. Ahlmann (1953) states that the ablation of glaciers is a function of the length of the ablation period, i. e. on the whole the period with temperatures above 0° C. Wallén (1948) has found that high summer temperature is the main factor favouring ablation.

If there is a proportionality between temperature and snow precipitation, the accumulation must increase with sinking temperature as long as there is some part of the year with temperatures above freezing (see fig. 6).

In this figure are shown three situations, represented by temperature curves. Curve 2 is obtained by lowering the values in curve 1 by 5° C, and curve 3 by lowering the values in curve 2 by 5° C. If the actual temperature follows curve 1 there will be accumulation of snow as long as the temperature is below 0° C. Some ablation due to melting will occur during the summer. If the temperature follows the

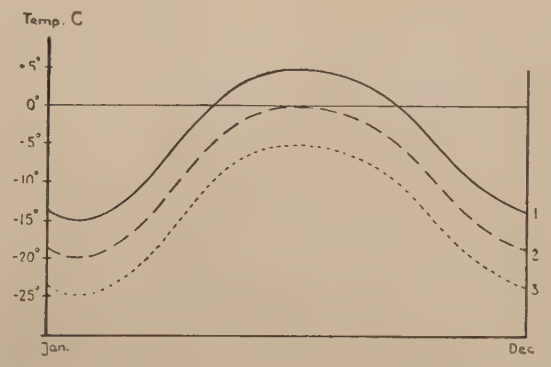

Fig. 6. Hypothetical curves for yearly temperature variation.

curve 2 accumulation will take place during the whole year and there will be no ablation due to melting. The net gain of snow will be larger in this case than in the case 1. When the temperature is lowered to curve 3 the accumulation will be smaller than in case 2 and there will be no ablation due to melting. The net accumulation in case 3 is then lower than in case 2. The ablation due to evaporation decreases with temperature as does the precipitation and therefore the decrease with temperature of the net accumulation may be assumed to be slow. In fact, according to Ahlmann it has been found by the Norwegian-British-Swedish Antarctic expedition 1949—1952 that there was still a positive net accumulation on a glacier when the yearly mean temperature was —40° C.

If the air temperature at e. g. the Kårsa-glacier, studied by Wallén, would sink 5° C, this would result in a shortening or disappearing of the ablation period. The length of the accumulation period is bound to increase and probably the total accumulation would also increase. There would accordingly be a net gain of ice on the glacier. We also know that the retreat of glaciers have taken place at the same time as air temperature has risen in higher latitudes in the last century. We therefore conclude that on the earth in general a temperature increase is followed by a retreat of glaciers.

Efforts have been made to explain the climatic changes as an effect of variation of the general circulation of the atmosphere. We know that at certain places the effect of the general circulation varies from one year to another, but normally an increase of temperature in one region is compensated by a decrease in another region. A world change of temperature persisting for many years claims for a physical explanation and as far as I can see can only be explained by a change in the general circulation due to a change of heat and cold sources in the atmosphere. It seems probable that a variation in the total solar energy is the main cause for these changes.

Willett (1949) attempts another approach. He considers the effect of the ultraviolet radiation which according to measurements varies considerably. Willett suggests that this variation of ultraviolet radiation is the cause of climatic fluctuations. The poleward motion of the subtropical highs as obtained from Serra's maps may be a result of a slightly increased solar radiation.

When the solar radiation energy increases it seems probable that the kinetic energy of the earth's atmosphere as a whole should increase. This increase of the kinetic energy must above all take place north of the subtropical high pressure belts and it is not clear in what direction the kinetic energy in the trade wind area should change. However it is possible that the effect of an increased solar radiation on the water flow in the Equatorial Counter Current may be a weakening of the flow. With the poleward shift of the subtropical highs a larger part of the westward wind-driven water current will pass polewards and give no contribution to the piling up of water at 5—10° N where the Counter Current starts. The piling up of water in the western part of the Pacific is also a complicated function of the pressure distribution over the eastern area which may change simultaneously with the trade winds. Anyway the low rate of accumulation of calcium carbonate at present time and in the specific area mentioned is found at a period of relatively high temperature on the earth's surface.

The most intense atmospheric circulation outside the trade wind belt is to be expected at periods when the solar radiation is increased at the same time as the polar regions are covered by ice and snow, and the weakest circulation is to be expected when solar radiation is decreased and there is yet no ice in the polar regions. The lag effect on the general circulation of snow and ice conditions in the

polar region and the lag effect of the heat capacity of the ocean water must, however, be considered small and only of importance when dealing with details of the history of past ages.

YEH, WALLÉN, and CARSON (1951) have studied the precipitation in Hawaii and state that the cyclonic weather type has become more frequent during the last 50 years then before. That would indicate that the center of the pressure high has shifted southwards during that time. However, as the authors mention, the increased number of observed cyclonic disturbances may also depend on the improvement of the synoptic network and of the analysis technique which certainly has taken place in the Pacific during the last half century. From Hawaii there is another observation of interest which seems more conclusive. It has been found (SELLING, 1948, p. 90) that the frequency of northeast winds in Hawaii has decreased in the past decades and that the frequency of easterly winds has correspondingly increased. This may be interpreted as a result of a northward shift of the high pressure area.

By analyzing the ratio of the light and heavy oxygen isotopes in calcium carbonate tests of foraminifera EMILIANI and EDWARDS (1953) have found that during Lower and Middle Tertiary the temperature of the bottom water was around 10° C whereas it is now close to zero. This shows that at that time temperature was much higher in the polar regions, where the equatorial bottom water originates, than the temperature is at present.

Further the isotopic measurements on the Pleistocene calcium carbonate accumulation maxima show a temperature of the planktonic foraminifera (from the surface layer of the sea) which is significantly lower than the shell temperatures in the adjacent calcium carbonate accumulation minima (EMILIANI 1954), thus confirming Arrhenius' interpretation of the carbonate maxima as cold water facies and the minima as warm water facies.

In conclusion I should like to say that the meteorological information that is available concerning the relation between climatic changes in high latitudes and the atmospheric circulation over the open ocean in low latitudes is not overwhelming. There is however, a slight indication that the trade winds have decreased at the same time as the temperature difference equator-pole has decreased during the last 80 years. It is also possible to accept that a decrease of temperatures over the whole earth may lead to an increased effect of the trade wind on the Equatorial Counter Current.

Arrhenius' theory of a link between the rate of accumulation of calcium carbonate at the bottom of the sea and the trade wind branch of the general atmospheric circulation is thus supported by some meteorological facts and it seems to me that there are no meteorological facts which definitely contradict the theory. Very important facts concerning the past climate have been obtained from work on the sediments collected by the Swedish Deep Sea Expedition and it is to be hoped that future studies of this kind will contribute to further progress in the complicated field of climatic changes.

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